Discovery, Invention and Innovation for Combating Irregular Warfare

The Twentieth Annual Strategy Conference

15 April 2009

Dr. John Parmentola
Director for Research and Laboratory Management

Purpose

- ***Recognize the importance of Irregular Warfare***
- ***Explain the synergistic benefits of realizing disruptive technologies through investments across key frontier areas of science***
- ***Provide examples from biotechnology of future disruptive technologies that can play a role in combating Irregular Warfare***

"The "strategic corporal" is a reality. We've moved beyond the mantra that every Soldier is a scout. Now every Soldier is an intelligence asset. What we do to empower that corporal will create more strategic advantage than anything I know."
— General Peter W. Chiarelli, Vice Chief of Staff of the Army

The Twentieth Annual Strategy Conference Questions

- ***In what ways can emerging technologies affect the strategic balance of power?***
  - ***Difficult to be specific, however, through timely opportunity advantage they will enable us to stay ahead of our adversaries.***

- ***How do strategy and technology interface within the defense establishment today?***
  - ***In large part, not much differently than it has in the past, but quick reaction capabilities have substantially responded to short –term requirements.***

- ***Which emerging technologies seem to hold the most potential?***
  - ***Generally, this is very hard to predict, however, currently there are seven areas that hold great promise.***

- ***How can the United States best develop alternative***

The Twentieth Annual Strategy Conference Questions (cont'd)

- ***How should U.S. defense strategy adjust?***
  - ***According to Secretary Gates, we need greater emphasis on Irregular Warfare.***

Irregular Warfare encompasses insurgency, counterinsurgency, terrorism, and counter-terrorism, raising them above the perception that they are somehow a lesser form of conflict below the threshold of warfare.

-- Irregular Warfare Joint Operating Concept, Sept. 11, 2007

DoD Irregular Warfare Policy Guidance

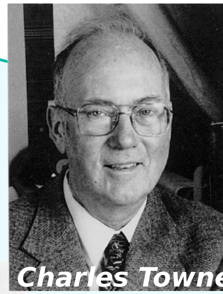
The USD(I) shall:

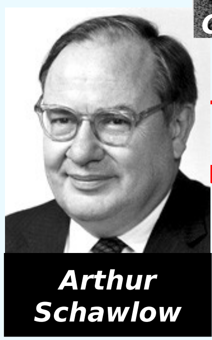
- ***…… guide the development of capabilities and capacity for persistent intelligence, surveillance, and reconnaissance and assessment of operational areas …………… improve all-source collection to identify irregular threats from state and non-state actors.***
- ***Ensure timely information dissemination from the strategic to the tactical level, recognizing that IW places particular reliance on releasable products to facilitate working with foreign security partners***
- ***Manage the development of appropriate analytical intelligence models, tools, and data to provide intelligence support to U.S. Armed Forces for IW***
- ***…… prioritize capabilities to identify, locate, track and target adversary networks, cells, and individuals***

The USD (P&R) shall:

- ***…… create opportunities for DoD personnel to develop foreign language proficiency and cultural knowledge***

All Great Discoveries and Inventions had no Customer



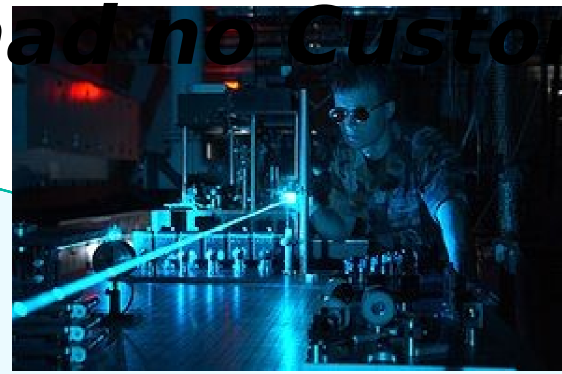


1954
Charles Townes and Arthur Schawlow invent the MASER

1958
Townes and Schawlow theorize the Optical MASER or LASER

1960
Theodore Maiman invents the Ruby LASER
Ali Jayan invents the Gas LASER

1962
Robert Hall develops the semiconduct or LASER, the most commonly used today



1972
Introduction of the Barcode Scanner

1974
LASER Disc Players

1980's
CD Players & LASER Printers

Widespread use of LASERs for commercial and military applications

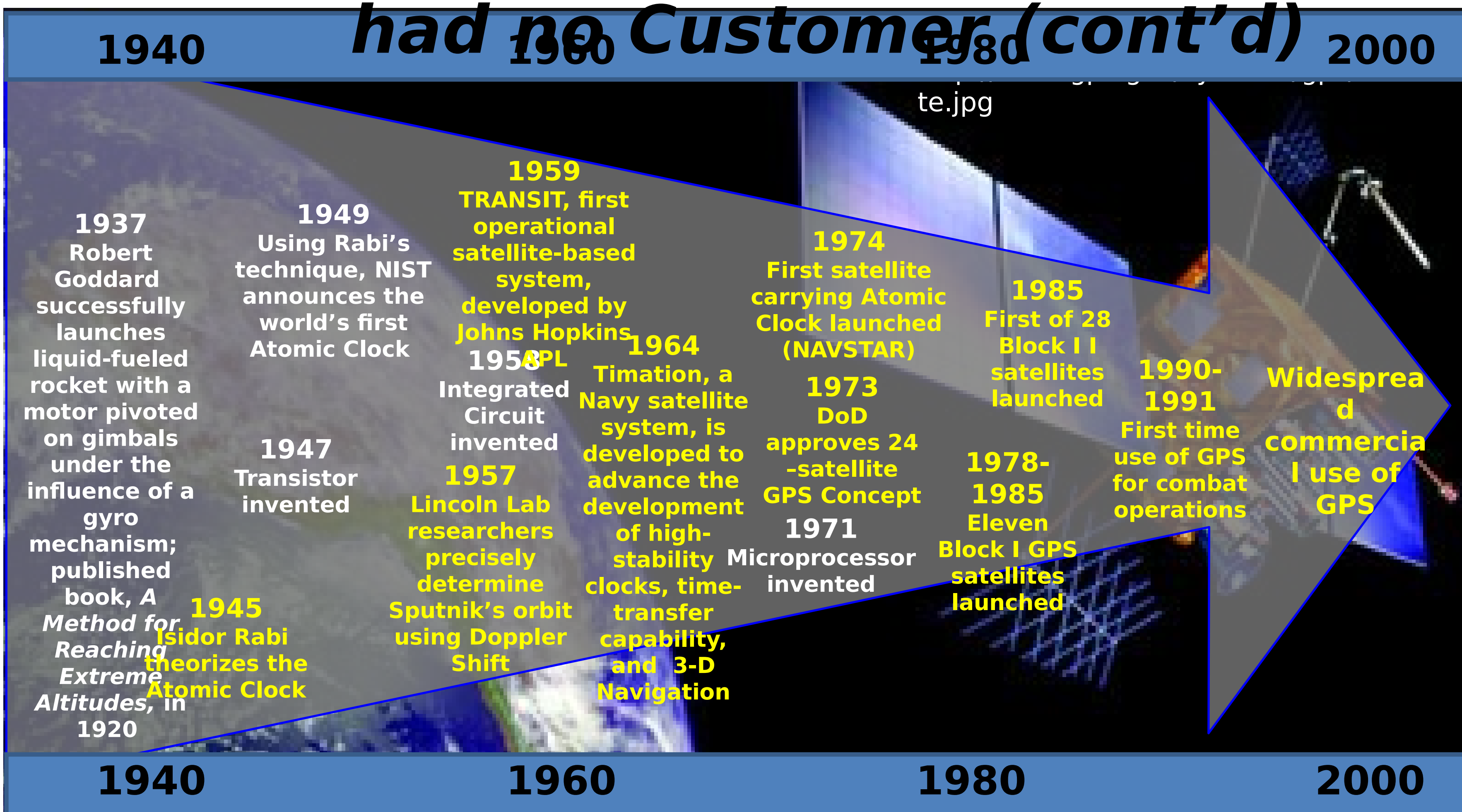
Lightweight Laser Designator
Photo from Defense Industry Daily

1950	1960	1970	1980	1990	2000

When the first laser appeared, scientists and engineers were not really prepared for it. Many people said that the laser was "a solution looking for a problem."

-- Charles Townes

All Great Discoveries and Inventions had no Customer (cont'd)



Every vision is a joke until the first man accomplished it; once realized, it becomes commonplace – Goddard's response to NY Times criticism, 1920

Technology Trends Creating Extraordinary Opportunities

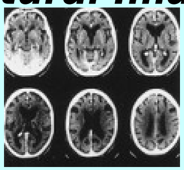
- ***Time compression***
  - ***Speed of light conveyance of information over long distances***
  - ***Rapid processing of information (ubiquitous availability of high performance computing)***
- ***Miniaturization***
  - ***The incorporation of more functions into smaller spaces will continue through a variety of methods and techniques***
- ***Complexity***
  - ***Creation of new materials from atomic level up with desired properties***
  - ***Understanding and controlling complex systems with great precision, e.g., complex networks both human engineered and biologically evolved***

Basic Research…

The Next Generation of Disruptive Technologies

Decade of the 1970's

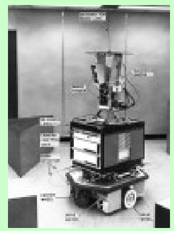
Structural Imaging



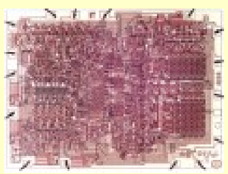
1971 – First Practical X-ray Computed Tomography Image

Artificial Intelligence

1970- Shakey the robot

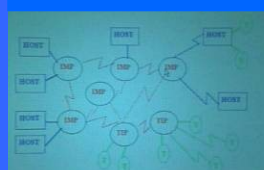


Micro- processors



1971 – First 4-Bit Micro-Processor in Production

Schematic of Early ARPANET

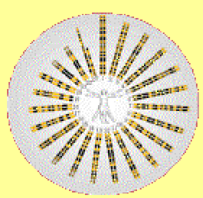


ARPANET

Super-computing

1975 – Cray I Supercomputer

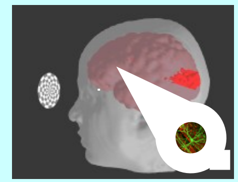
Arcade Games



Genetic Engineering

Today for 2020 and beyond…

Functional Brain Imaging & Beyond

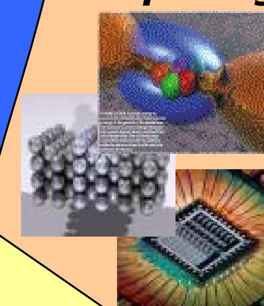


Robotics

Nano-technology

Networ k Science

Quantum Computing



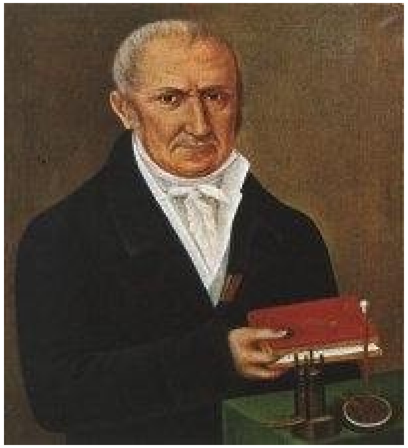
Immersive Environments

Bio-technology

Why Emulate Biological Systems?

- ***Nature develops through evolution optimal solutions to practical problems***
- ***Understanding these solutions in terms of physical mechanisms and engineering principles can enable innovation***
- ***Recent breakthroughs in genetic engineering provide the ability to change the genetic blueprint of "factory cells" to develop novel solutions previously unattainable in nature***

Alessandro Volta and the Torpedo F



- ***Volta read about the torpedo fish that can deliver a powerful electric shock by means of its electric organ that is comprised of alternating discs of material***

- ***In 1800, by imitating the electric organ of the torpedo fish, Volta invented the first electrical pile: an alternating series of discs of zinc,***

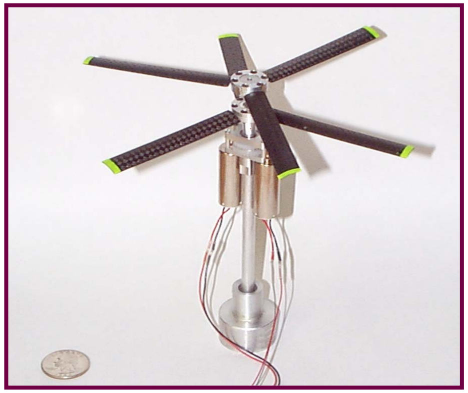
Combat and Soldier System Survivability

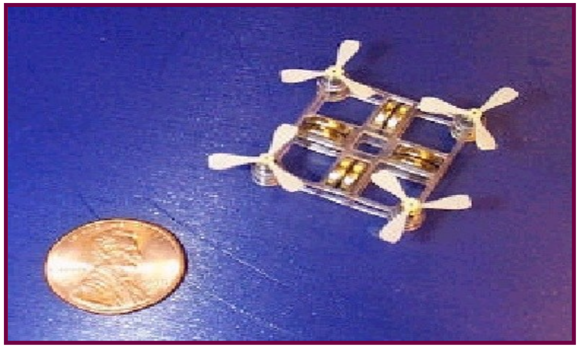
- ***Develop new robotic vehicles for Soldier protection***

- ***Keep Soldiers out of dangerous places***

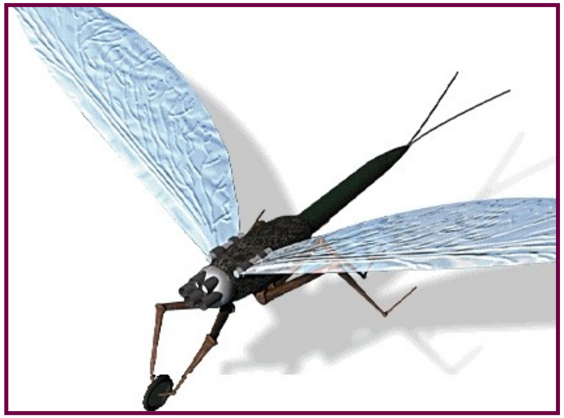
- ***Use unmanned systems to go into places where soldiers cannot go***

Micro Robotic Systems that Mimic Nature





- **Mimic insects that acquire information through sight, smell, taste, touch, temperature, pressure**
  - **Develop “brains” that process and store information which then regulate:**
    - ✓**Navigation**
    - ✓**Propulsion**
    - ✓**Pitch, yaw and roll**
    - ✓**Movement on surfaces**
    - ✓**Communications**



Nanoflyer - Petter Muren

Focus is on biologically-inspired systems

Nature's Remarkable Small Flyers

The Bumblebee (weight = 0.002 - 0.02 oz)

- Enormously maneuverable system
- Horizontal thrust >5x its weight
- Payload = 100% body weight (nectar)
- Holds image velocity of landing surface constant on approach (zero velocity at touchdown)

The Dragonfly (> 300M years old; weight = 0.01 oz)

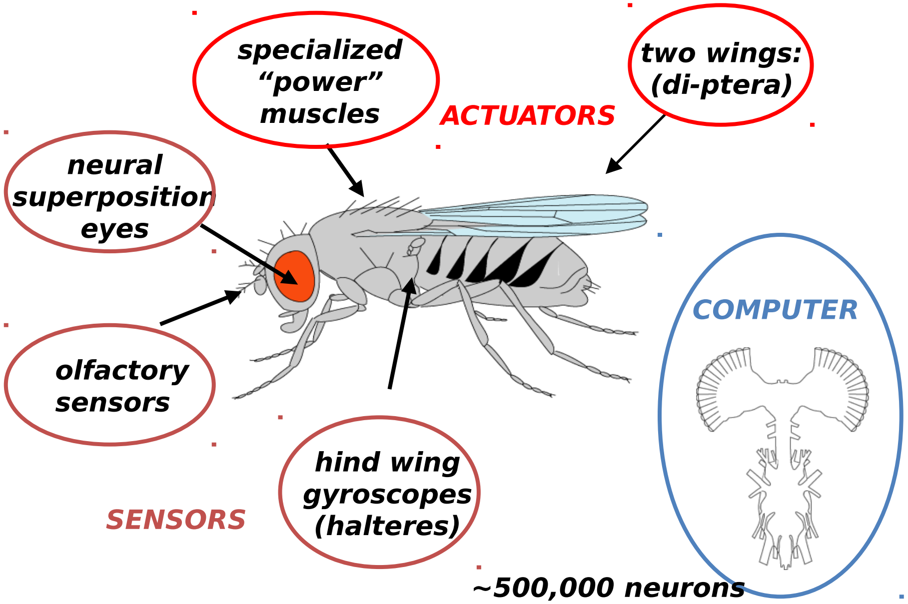
- Flies at speeds up to 30-60 mph
- Wings work independently – can hover and change direction instantaneously
- Short wing strokes + unsteady-state airflow allow forward & backward flight at hover while horizontal
- Voracious appetite – seeks and eats insects on the fly

The Hummingbird (weight = 0.1 oz)

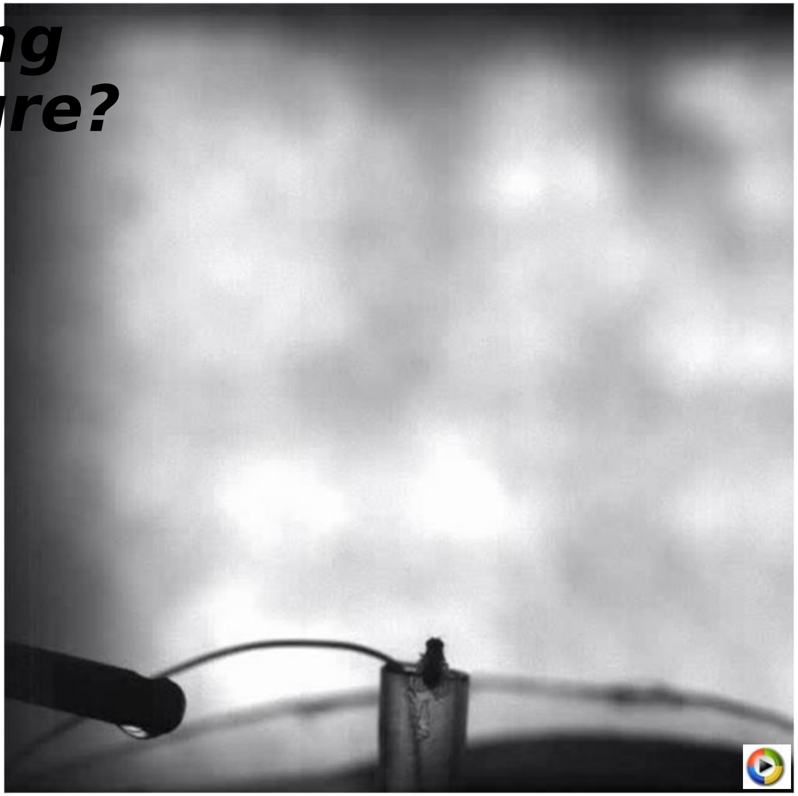
- Only bird that can hover with body motionless – but requires excessive energy to sustain
- Consumes ½ its weight in sugar daily from nectar
- Generates thrust from both down beat & up beat – wings perform a figure 8 in hover
- Endurance: 800 km migration across Gulf

Insect Flight Control

- **Challenge: Coordination of complex elements of flight control system:**
  - *Integrated sensing, actuation and control*
  - *Amazing robustness, performance, flexibility*
- ***What is the decision-making architecture?***

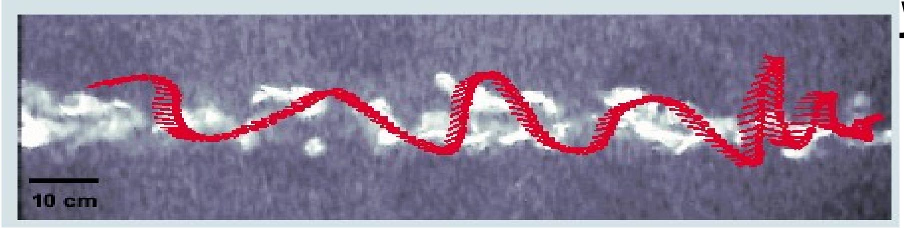


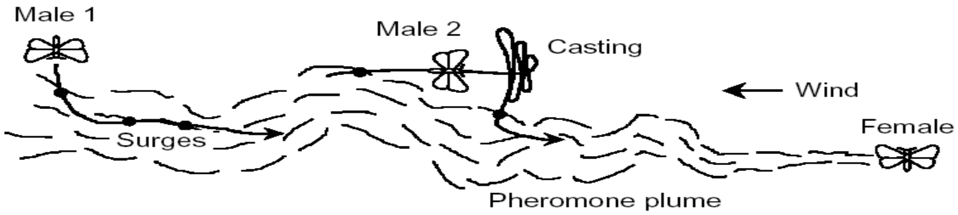
Dickinson Lab, ICB, Caltech



Moth Sense and Control System

- ***Biological sensors exhibit unequaled sensitivity, specificity, speed and refresh-rate***
  - ***The chemical sensors of the moth can detect a single molecule of the sex pheromone***





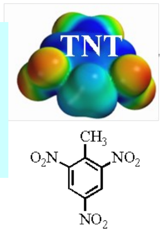
Bazan lab, ICB, UCSB

- ***Signal amplification mediated by elements that fit together by precise lock-and-key molecular recognition***

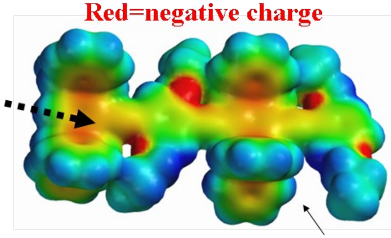
Remote Explosive Detection

Molecular engineering

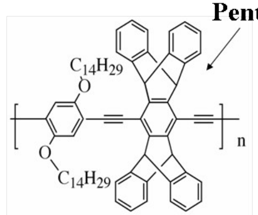
Blue=positive charge



Red=negative charge

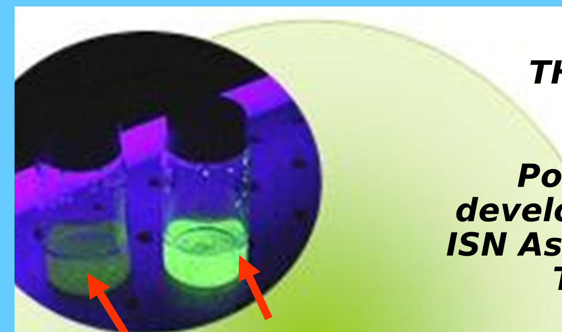


Pentiptycene



Design Attributes:

- Highly selective to only TNT and DNT
- Highly resistant to contamination
- Long-term stability for reuse



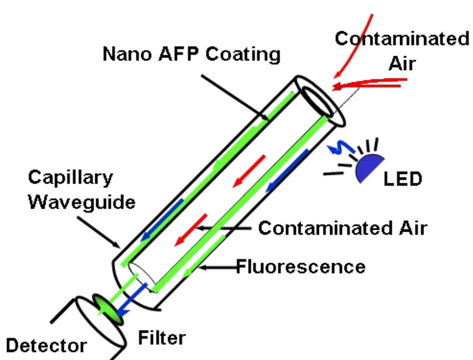
No TNT

TNT Detected

THE SCIENCE:* *Amplifying Fluorescent Polymer (AFP) developed by MIT ISN Associate Dir. Tim Swager normally glows green, but quenches when TNT is present.

- Rugged
- Handheld
- Lightweight
- Easy to operate
- Audio and visual indications

Integrated Detector/Sampler



First FIDO units in Iraq for evaluation (2005)

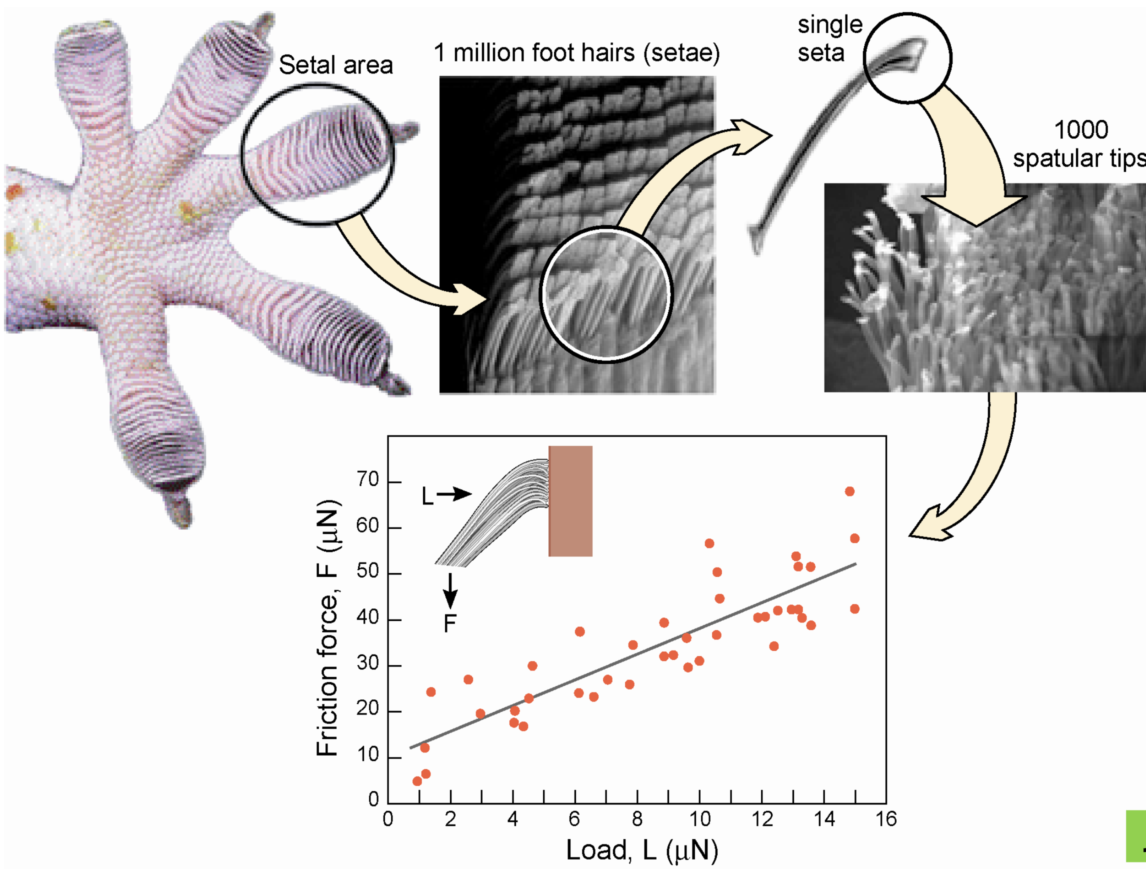
integrated on PackBot robots

Fido X and XT models

Fido selected one of Army's 10 Greatest Inventions for 2005
FidoPackBot selected one of Army's 10 Greatest Inventions for 2006

Biomechanics of Gecko Movement

Challenge: ***To mimic gecko biomechanics and adhesion that allows its feet or toes (pads) to strongly adhere to a surface and then detach within 10 milliseconds, thus enabling the animal to move rapidly on most surfaces, including walls and ceilings***

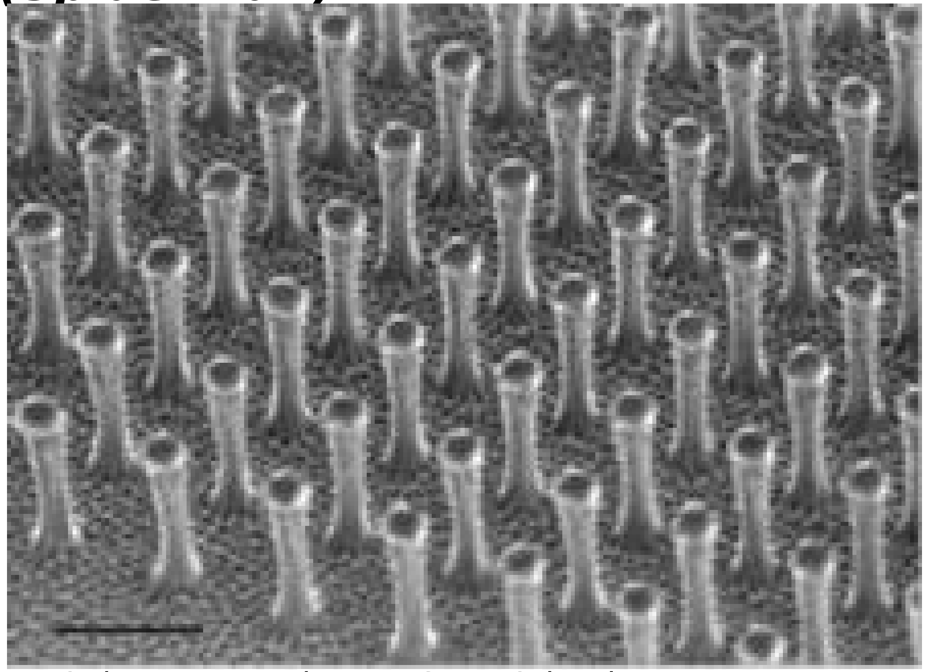


- ***Strong adhesion appears to be produced by "high tension" pulling in the adhering pads, which is quickly changed to very weak adhesion by the relaxation of the tension and peeling away of the setae from the extremities***
- ***It should be possible to mimic this process in mechanical or robotic devices***

J. Israelachvili, B. Gourdon, Q. Lin (ICB)

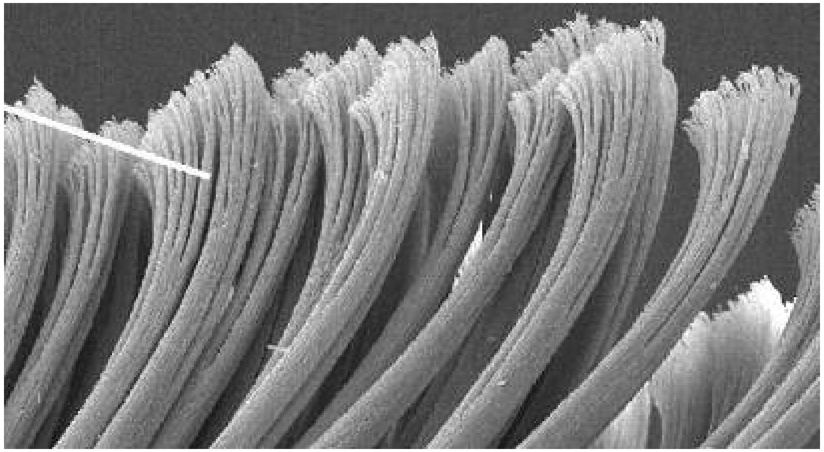
Mimicking the Gecko

"The use of a soft rather than solid base has dramatically (by nearly 1,000 times) improved gecko tape to support the weight of a suitably light familiar object (Spiderman)."

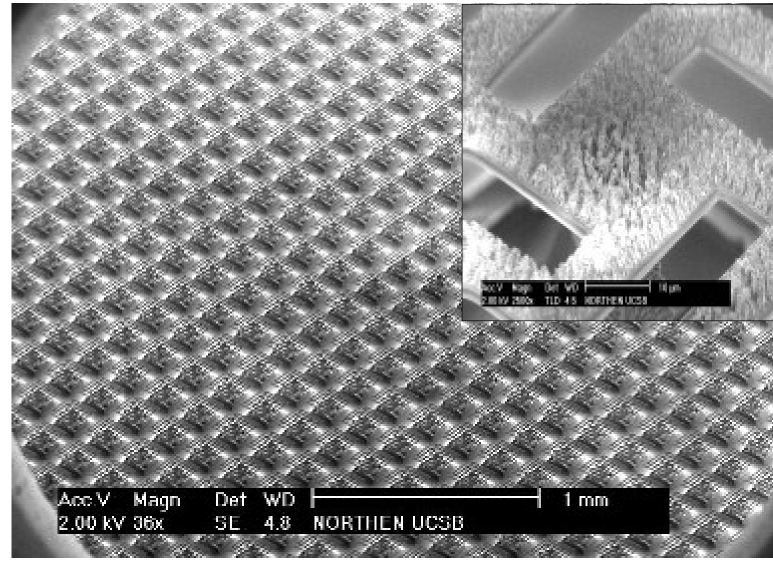


Geim, A. K., Dubonos, S. V., Grigorieva, I. V., Novoselov, K. S. & Zhukov, A. A. Nature Materials ***2****, 461-463 (2003)*

Mimicked?



Courtesy Eduard Arzt (S. Gorb)



Gecko > 300 Pa (Adhesion)

90 kPa (Frictional Adhesion)

Synthetic < 30 Pa (Adhesion)

$$m' = F_{adhesion} / F_{preload}$$

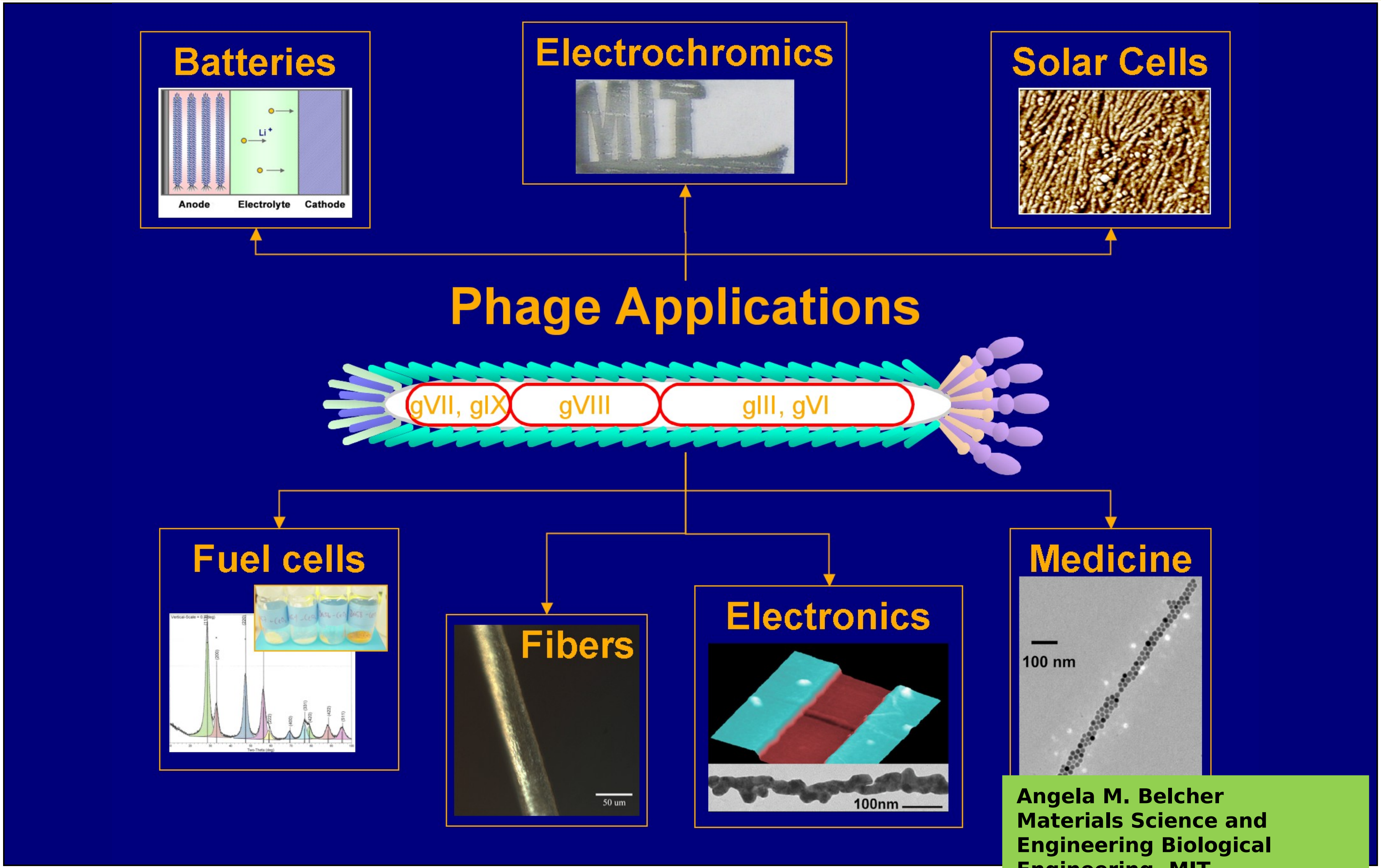
Geim et. al → m’ = 0.06

Northen & Turner → m’ = 0.125

Gecko → m’ = 8-15

Kimberly Turner and Michael Northen* Mechanical Engineering Department *Materials Department University of California, Santa Barbara

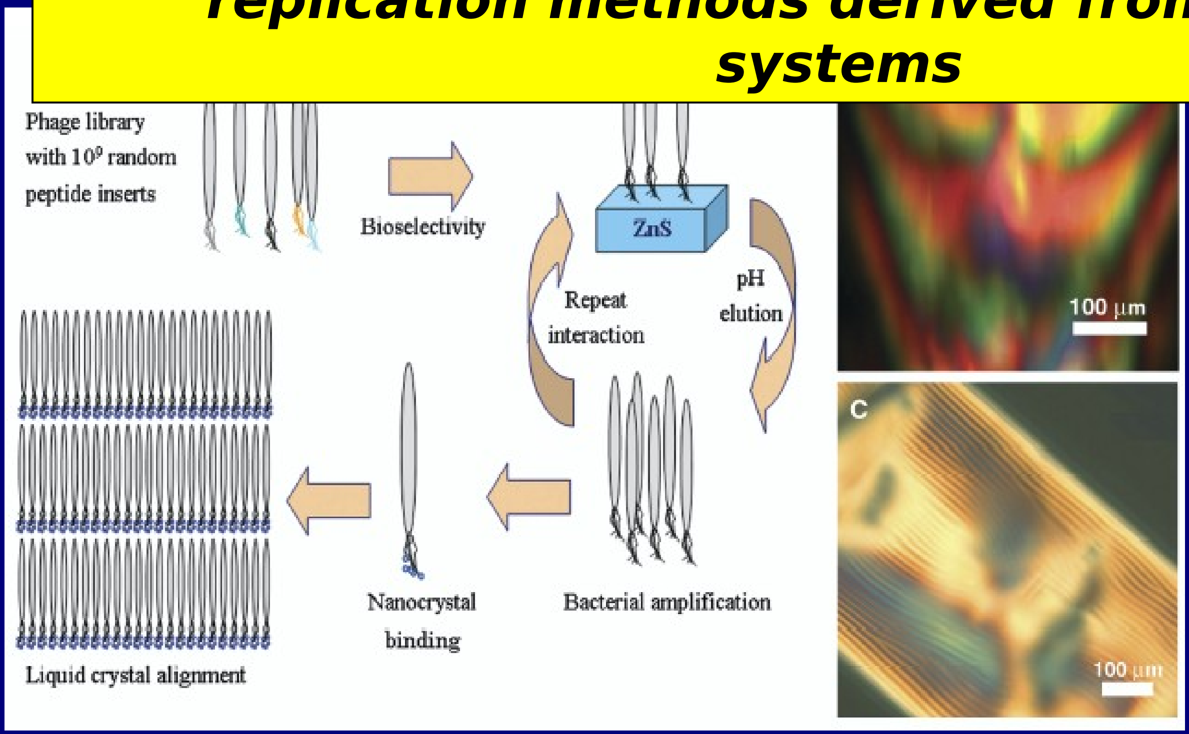
Biotechnology
- Phage Applications -

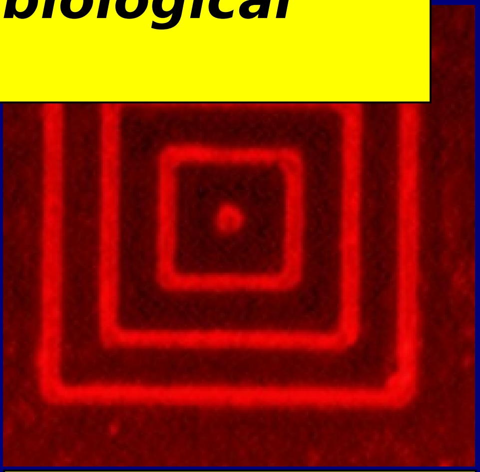


Angela M. Belcher
Materials Science and Engineering Biological Engineering, MIT

Nanobiotechnology for Advanced Electronic and Magnetic Materials

Material manufacturing using self-assembly and high fidelity replication methods derived from biological systems





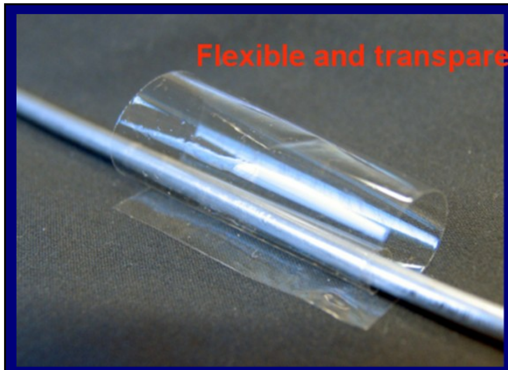
Fluorescent-labeled G12 Phage clone bound to GaAs pattern surrounded by SiO2

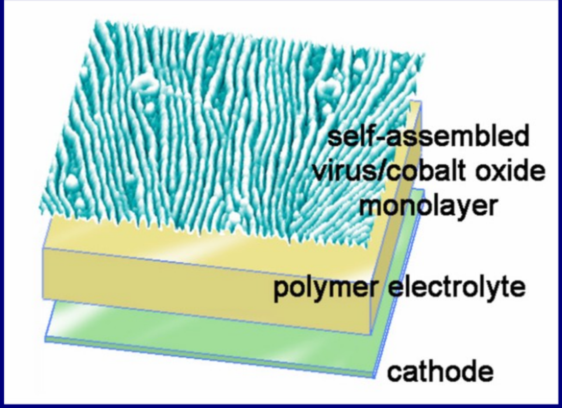
- ***Reduced feature size relative to current lithographic methods***
- ***Greater density of higher quality IC elements***

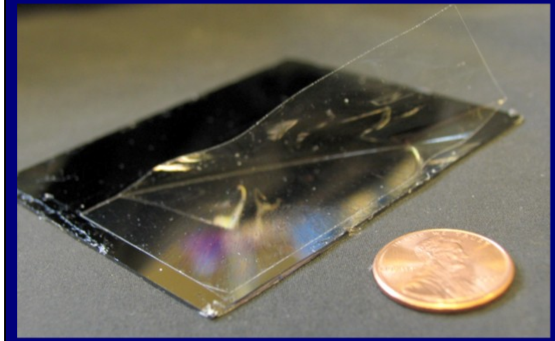
information processing

Angela M. Belcher, Materials Science and Engineering Biological Engineering, MIT

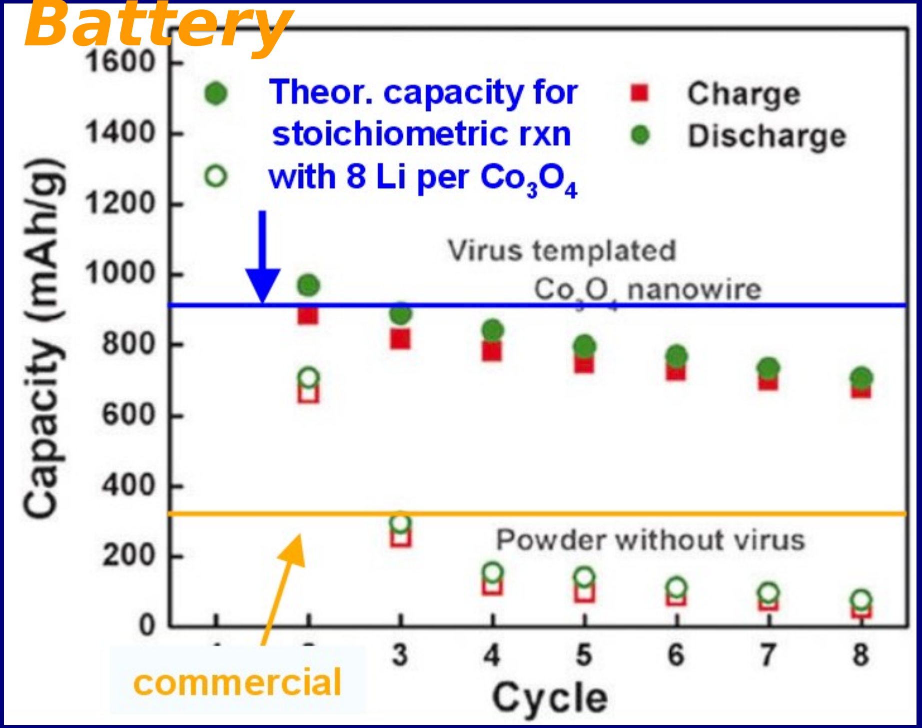
Biotechnology
- Virus Assembled Battery -

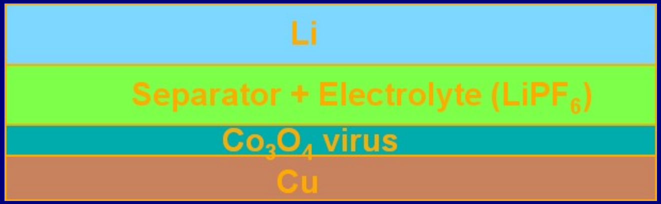






Virus Assembled Battery

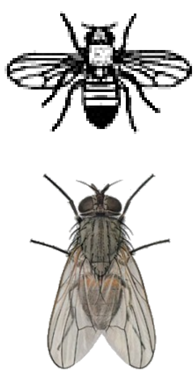


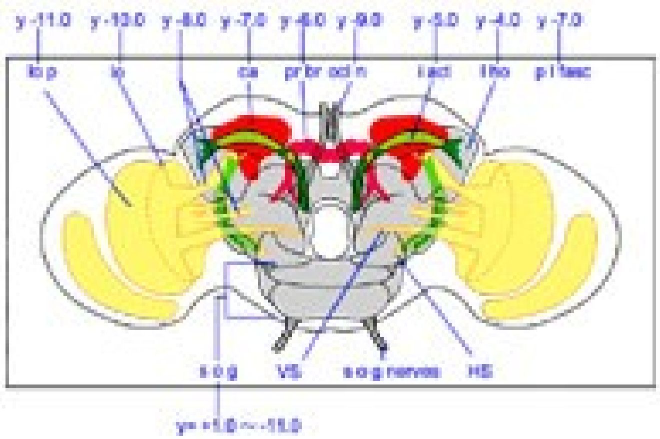


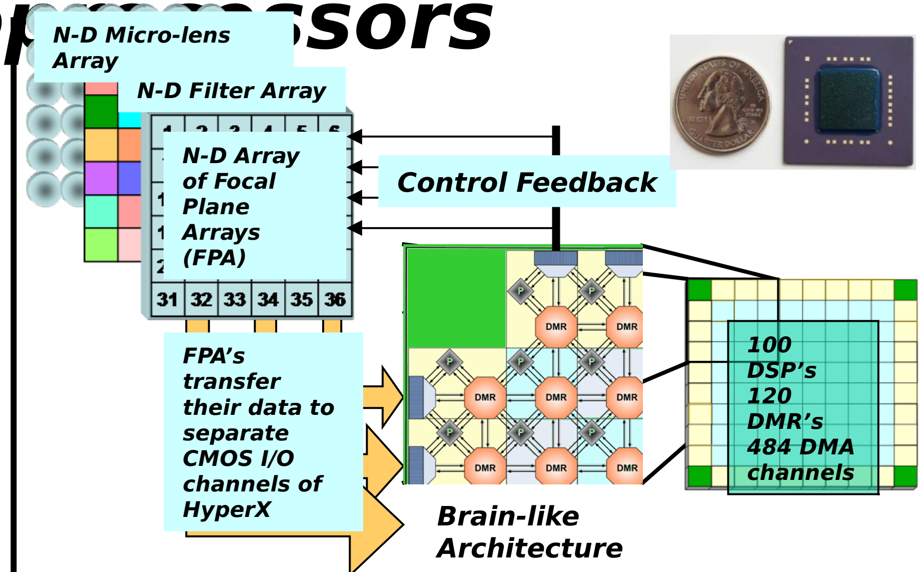
Improved rate capability

Angela M. Belcher
Materials Science and Engineering Biological Engineering, MIT

Computational Performance of the Fly vs. Current Microprocessors







- 300,000 neurons
- 5 milliseconds reset time
- 6 x 10^7 cycles/second
- Fly brain volume = 5 x 10^{-5} cc
- Cycle density = 1000

- HyperX Chip
- Consumes 1 Watt at 1 Volt
- 50 x 10^9 instructions/second
- Chip volume = 3.2 cc
- Cycle density = 15.6

Social Insect Networks

- ***Self-organization through insect sensing and communication***
- ***Multiple levels of organization***
  - ***social hierarchy and division of labor***
- ***Hubs, like the queen bee, distribute information through a dense network***
- ***Robustness***
  - ***Mass action of responses through***

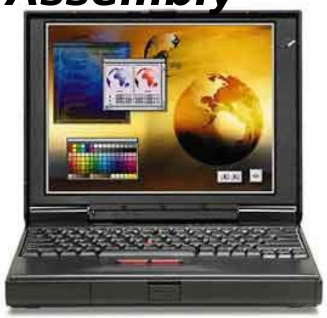
African honeybees in attack mode

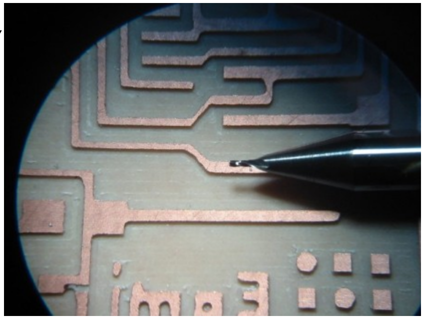
Jennifer H. Fewell, Social Insect Networks, Science Magazine, 26 September 2003

Alarm pheromone by a few guards cascades within a minute to stinging responses by thousands of bees

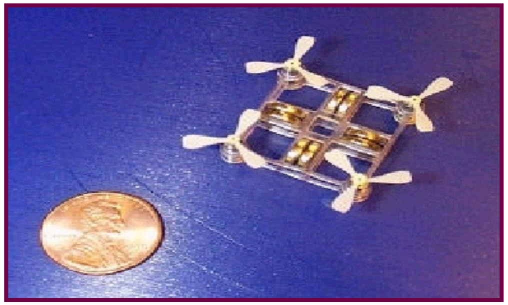
Digital Design and Manufacture for Field Fabrication of Micro Robotic Systems

Design Tools → Materials → Manufacturing → Assembly



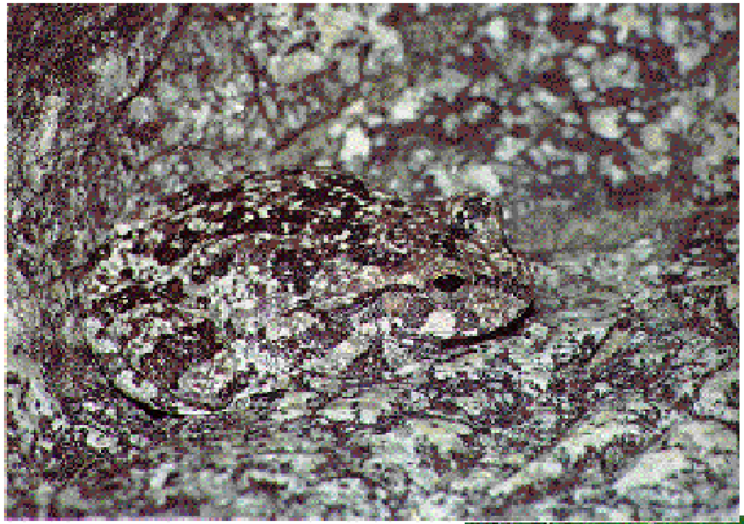



– *Aeromechanics*	– *Metals*	– *Laser cutter*	– *Insert*
– *Rotor design*	– *Silicon*	– *Milling machine*	– *Snap together*
– *Propulsion*	– *Plastics*	– *Focused ion beam*	– *Braze*
– *Flight control*	– *Composites*	– *Water jet*	– *Glue*




Professor Neil Gershenfeld, MIT

Built-in Survivability of Biological Systems



Where's the Toad?

Is this a fly or a bee?

lfogel@natural-selection.com

Adaptive, Flexible, Multifunctional Arrays

Dynamically adaptive camouflage driven by unique biomolecular mechanisms changing reflectance, color and texture

with ARL, NSC, IST inc., Computational Sensors inc & Roger Hanlon @ MBL

Flexible Display Center

Develops flexible display technologies for affordable, lightweight, rugged, low power and re ispl

- Wearable, light weight rugged displays

- Facility and pilot line Tempe, AZ

- Portable & rugged displays

Convergence of Scientific Understanding

- Miniaturization
- Wireless Communications
- Processing Speed
- Computer Memory
- High precision printing technology

Technology trends are converging to mature this paradigm shifting technology

Sense and Response

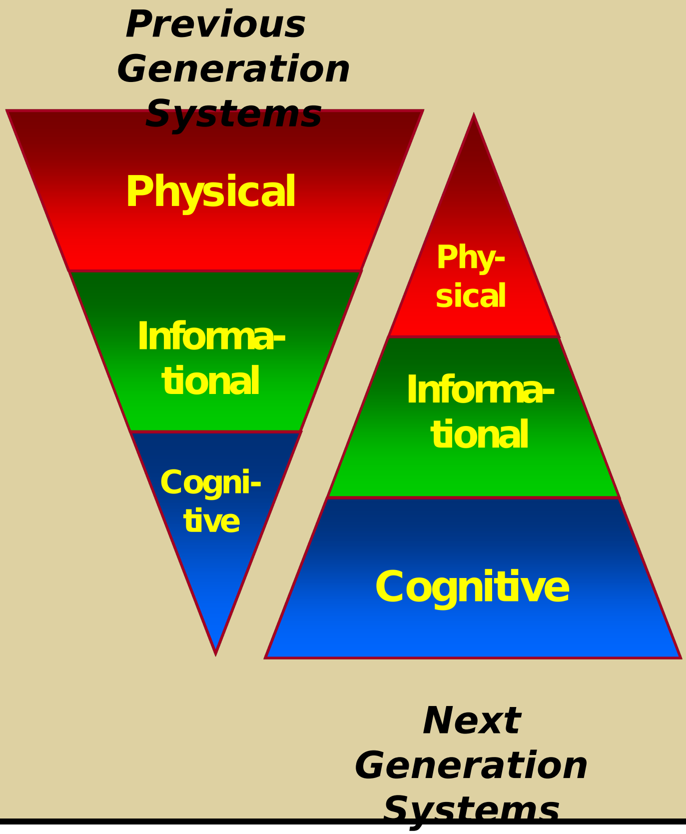
Trends

- ***Computers as we know them will disappear – incorporated into flexible materials***
- ***Miniaturized sensors will also be incorporated into flexible materials***
- ***Further advances will be made in light-emitting devices (OLEDs and PLEDs) that are highly efficient and printable***
- ***Flexible materials made of active control***

laterials that change color and morphology in response to environment or demand

Understanding Changes in Battlefield Dynamics

Changing Demands on Soldiers



Human Dimension

Challenge:

- ***Today's complex battlefields require the rapid and dynamic allocation of workload and responsibilities across Soldiers and place unprecedented demands on warfighters' sensory, motor, affective, & cognitive systems***

Goals

- ***Reduce training requirements, and operator injury, error, and hazards rates***
- ***Develop novel and effective human-system integration***
- ***Improve human-system performance***

Dimension of the Challenge

- ***In FY08, over 500,000 individuals were trained at Army-run installations and schools***
  - ***Variable learning capabilities (humans acquire, assimilate and make sense of infor***
  - ***Changes in battlefield dynamics have changed training requirements, more cognitive/less phys***
  - ***Need for Multi-skills capability (training acros Military Occupational Specialties, e.g. artillery who has to learn infantry tactics)***

e size does not fit all when it comes to training & learning

Creating a Virtual Human

- *Incorporate dynamics of human thought process, communication and response*
  - *Speech recognition*
  - *Natural language processing*
  - *Dialogue management*
  - *Cognition*
  - *Perception*
  - *Emotions*
  - *Animation*
  - *Cultural attributes*

SGT Blackwell - Soldier Avatar

Ultimate research challenge: Understanding who we are as humans

Virtual Humans
- Training Negotiation Techniques -

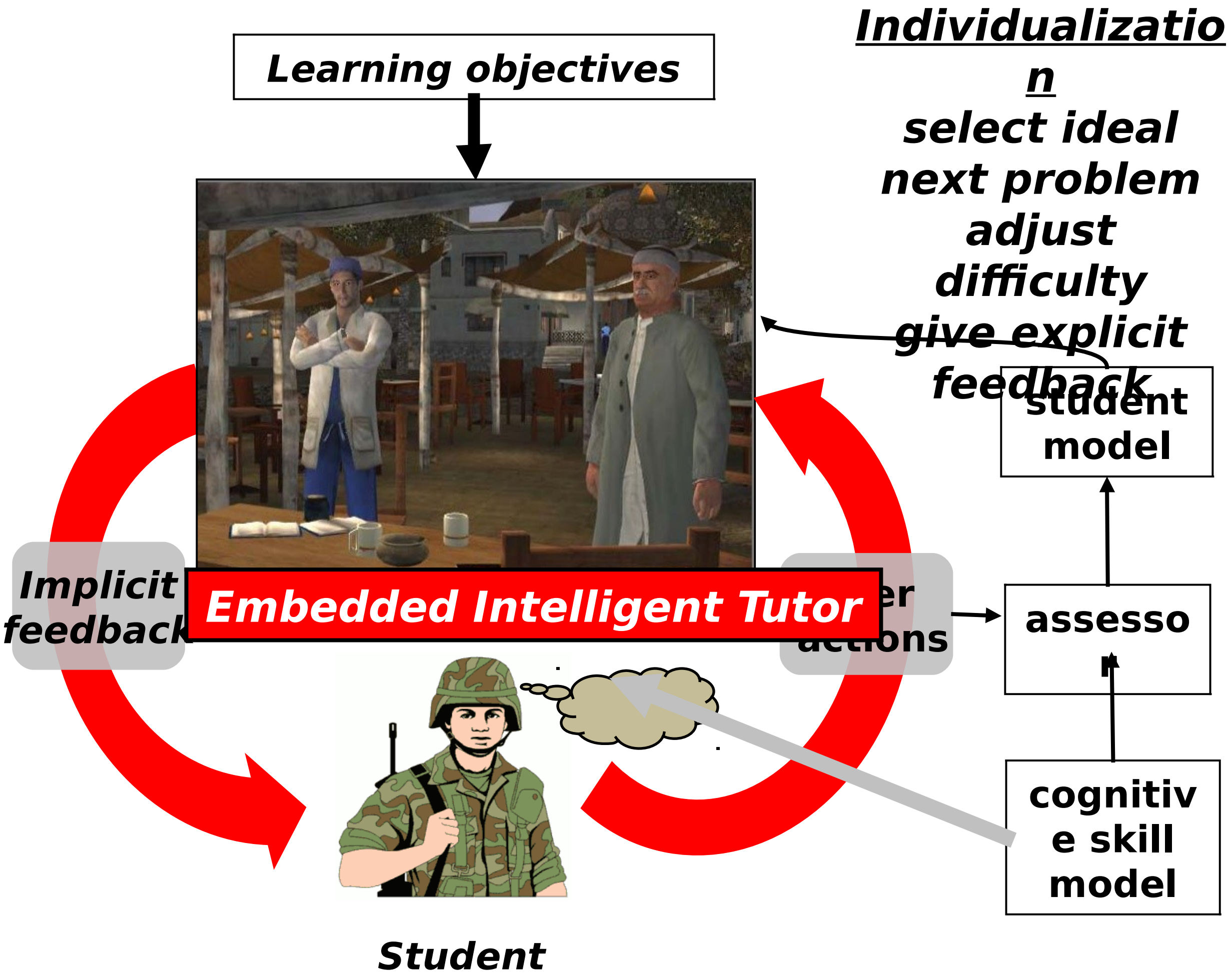
Training Goal:
Multi-party negotiation

- **Recognize and respond to a variety of negotiation tactics**

Interpersonal-skills training

- **Cross-cultural negotiation**

Tailoring Training & Learning in a Virtual Environment



- *Action-level assessment requires a model of the skill being taught to do plan recognition*
- *Individualized learning requires pedagogical models*
- *Student modeling research is*

Are there other inputs that could make this more effective & efficient?

Behavioral Science Assessments

- ***Pre- and post-testing used to verifying the effectiveness of training***
- ***Current methods include:***
  - ***SAT & ACT (college entrance exams) are correlated with first year grades in college (range of correlations across multiple data sets r=0.5 to 0.8)***
  - ***By adding additional criteria (e.g., high school grades), the predictive validity can be increased by approximately r=0.10***
  - ***Armed Services Vocational Aptitude Battery is correlated with SAT scores (r=.82)***
  - ***Armed Forces Qualification Test (AFQT) scores predict subsequent Advanced Individual Training (AIT) exam scores (a measure of how well Soldiers did in job-specific training)***
  - ***Tailored Adaptive Personality Assessment System (TAPAS)***

How can the assessments be done in real-time to enable truly adaptive learning environments?

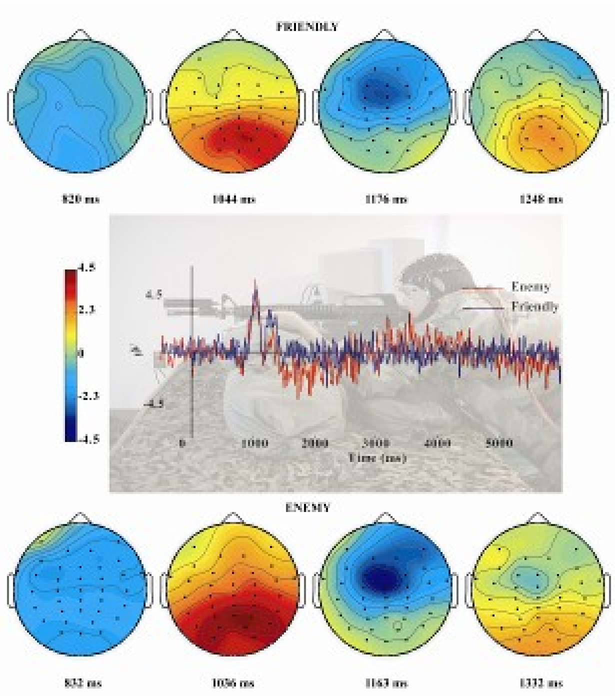
Neuroergonomics

Neurofeedback for Training

Accelerate training with real-time feedback of performance based on:

- ***Central and peripheral nervous system activity***
- ***Physiological activity***
- ***Behavior***

Expertise is accelerated by providing trainers techniques for optimizing levels of neural activity based on the unique variations in brain functioning



Adaptive Displays

Cognitive state assessment system to detect:

- ***Information overload***
- ***Lapses in attention***
- ***Arousal/fatigue***
- ***Presence of targets***
- ***Brain injury***

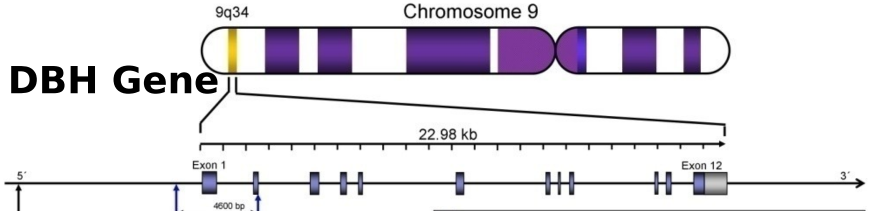
Mitigation strategies:

- ***Adaptively change displays to enhance situational awareness***
- ***Prioritize and schedule communications***
- ***Adaptively activate multimodal displays and alerting cues***
- ***Verify target detection and ID***
- ***Estimate range of targets and prioritize targets to engage***

Predicting Memory and Decision-Making Efficiency

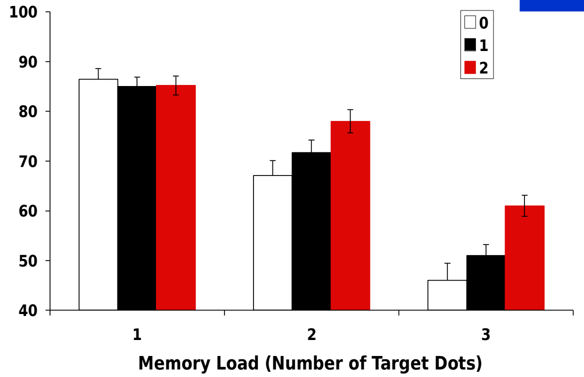
- ***The Dopamine Hydroxylase (DBH) Gene Predicts Working Memory and Decision Making Efficiency in Command and Control Under Automation***

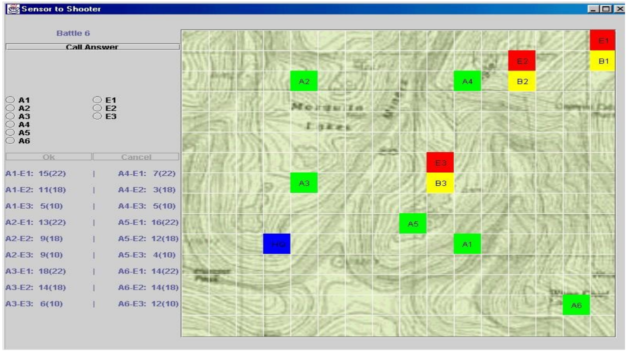
DNA Acquisition and Genotyping

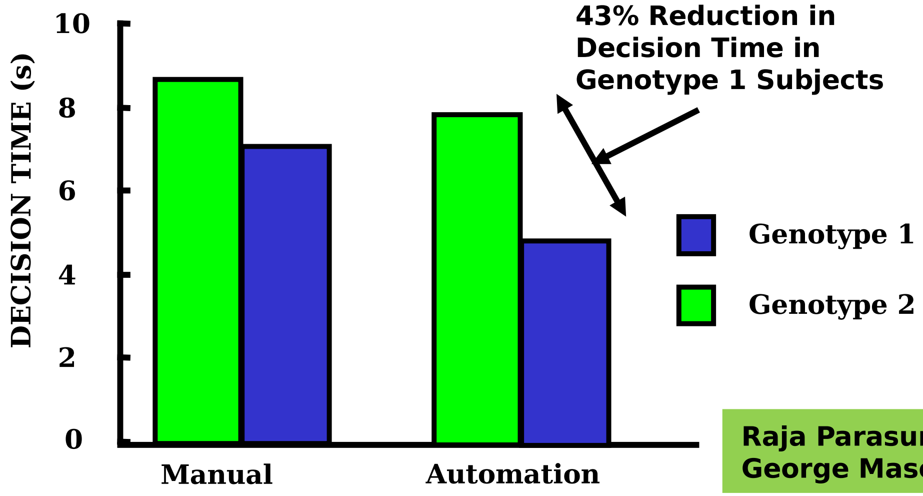


- ***Dopamine beta hydroxylase (DBH) gene product converts dopamine to norepinephrine in the brain***
- ***DBH modulation selective for prefrontal cortex dependent functions: working memory and executive attention***

G Allele Dose of the DBH 444 G/A SNP Predicts Working Memory



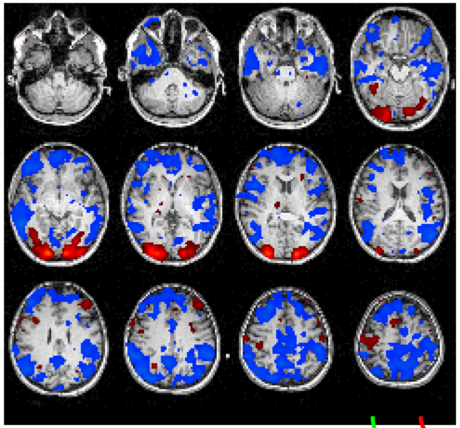




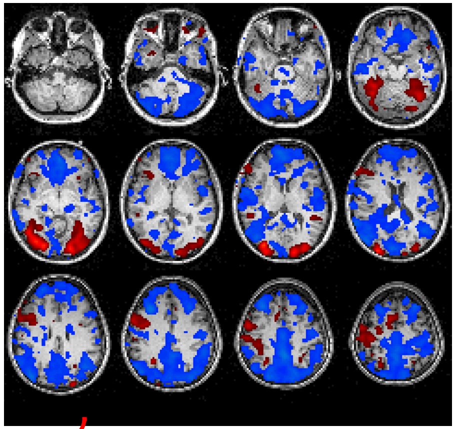
Raja Parasuraman,
George Mason University

Visualizers vs. Verbalizers

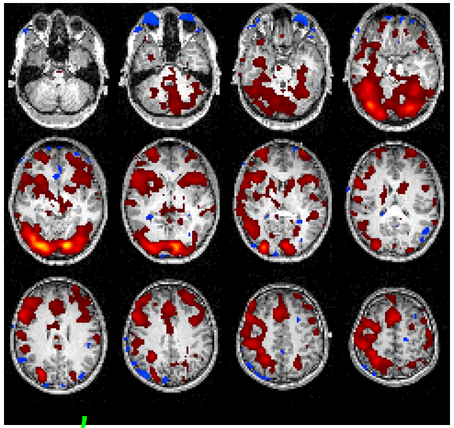
Visualizer 1



Visualizer 2



Verbalizer



r = .436

r = .298

Factors to be analyzed:

- *-tendency to visualize*
- *-tendency to verbalize*
- *-retrieval bias*
- *-memory performance*
- *-anatomical similarity*
- *-white matter connectivity*
- *-baseline brain activity*
- *-gender & ovarian hormone levels*
- *-personality factors*
- *-executive function skills & capa*

Scott Grafton, ICB

What factors can explain the similarity or dissimilarity between any two individuals' pattern of brain activity?

It's All About Efficiency and Effectiveness

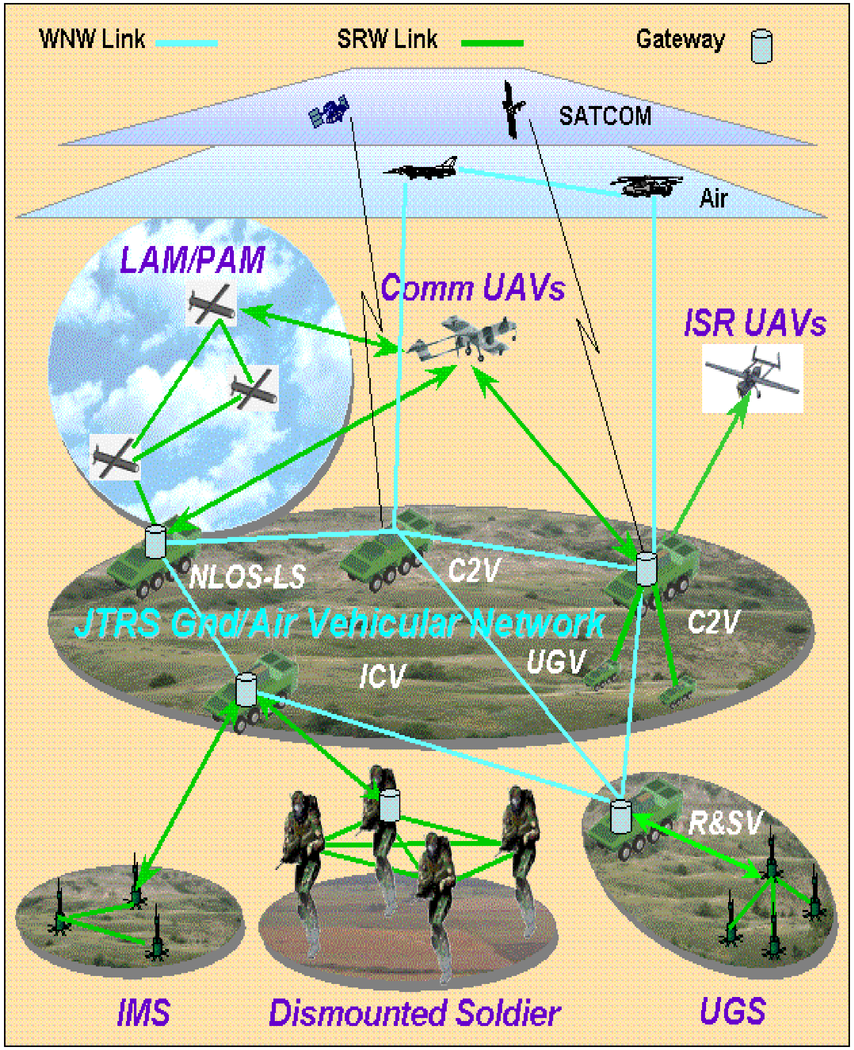
- **_Explore basic research in neuroscience, neuro-ergonomics, behavioral science and genetics to identify human specific characteristics that are measureable and could be used to design more effective and efficient training and learning systems for Soldiers_**

- **_Use virtual worlds as an experimental laboratory to validate individual human characteristics that are predictive in terms of efficiency and effectiveness of training and learning_**

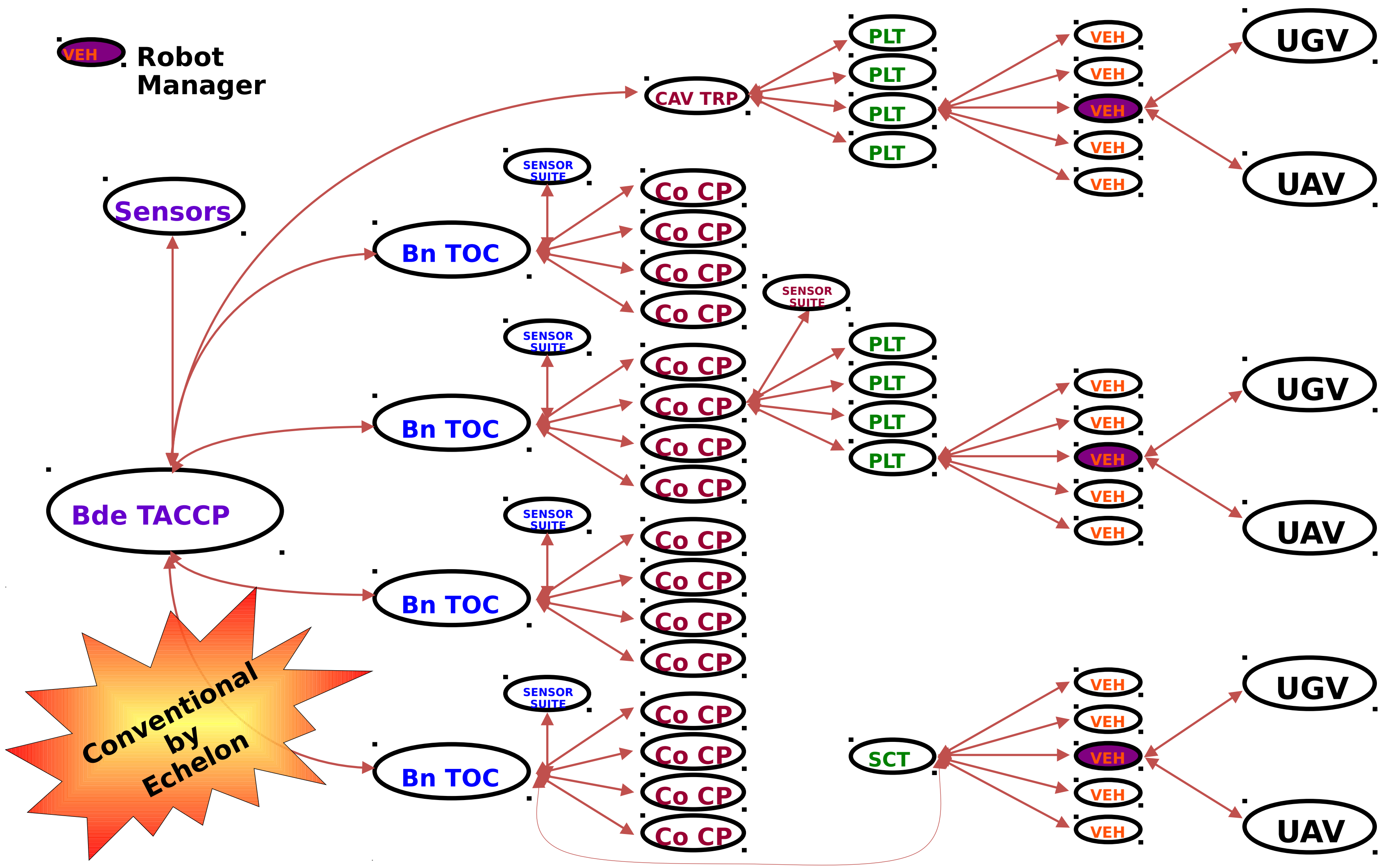
- **_Exploit intelligent tutors that adapt training ... characteristics_**

Individualized tutorial training is more effective than one size fits all classroom training

Network Centric Operations

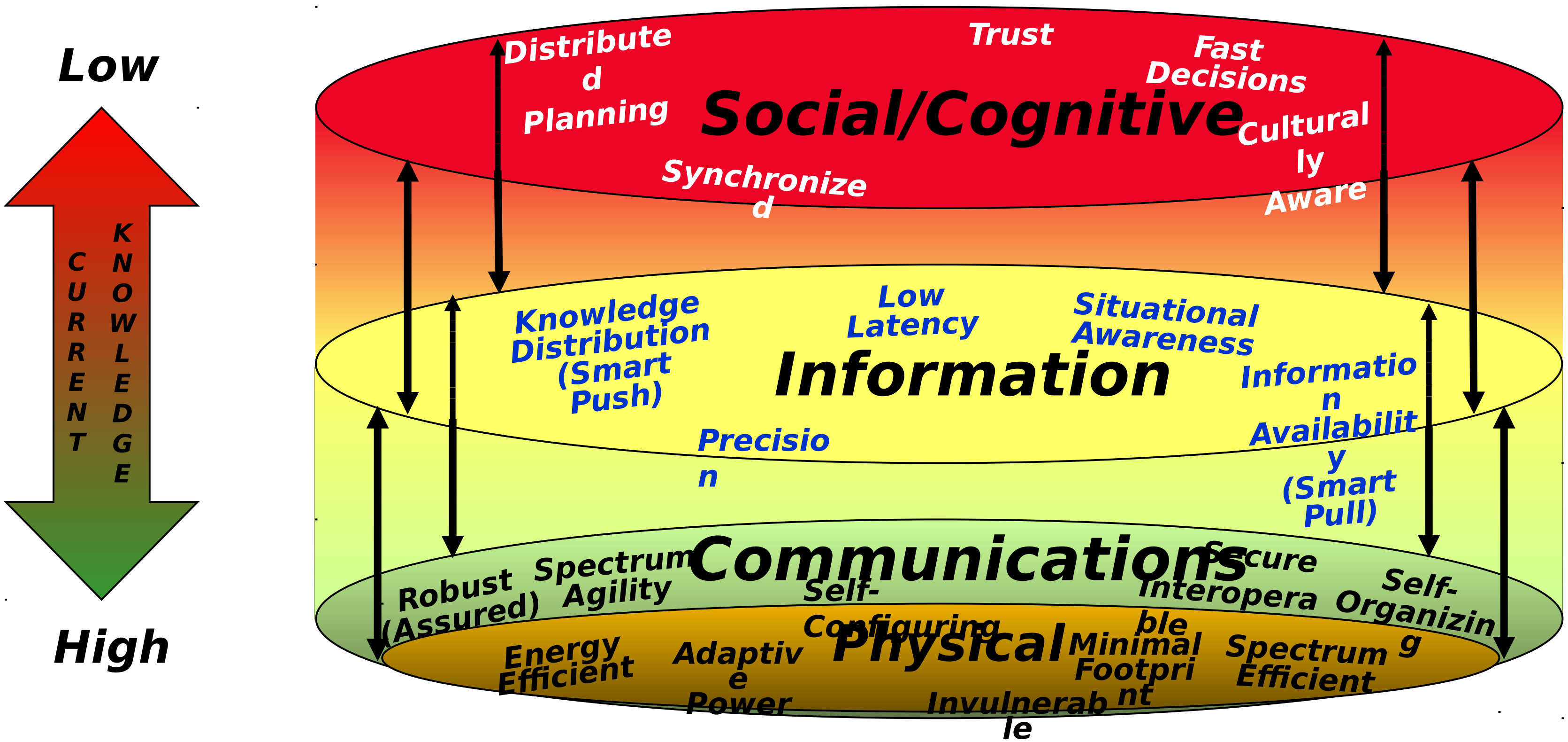


Conventional C³ Hierarchy



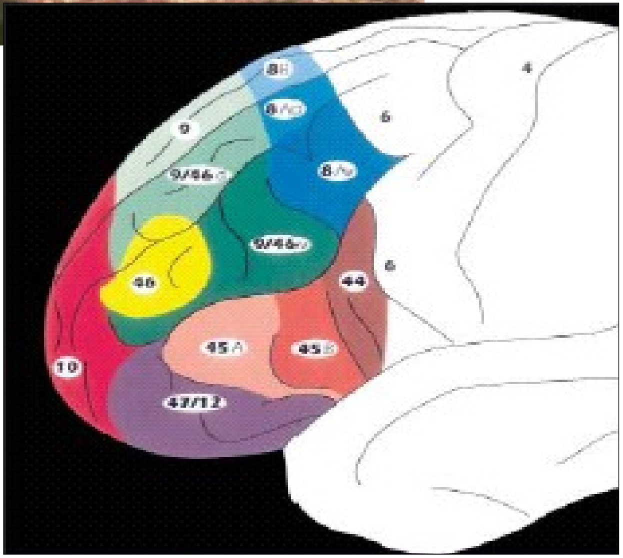
Interactive and Mutually Interdependent Networks

Command and Control ⇄ Collaborate and Connect



Current ability to predict network performance is limited!

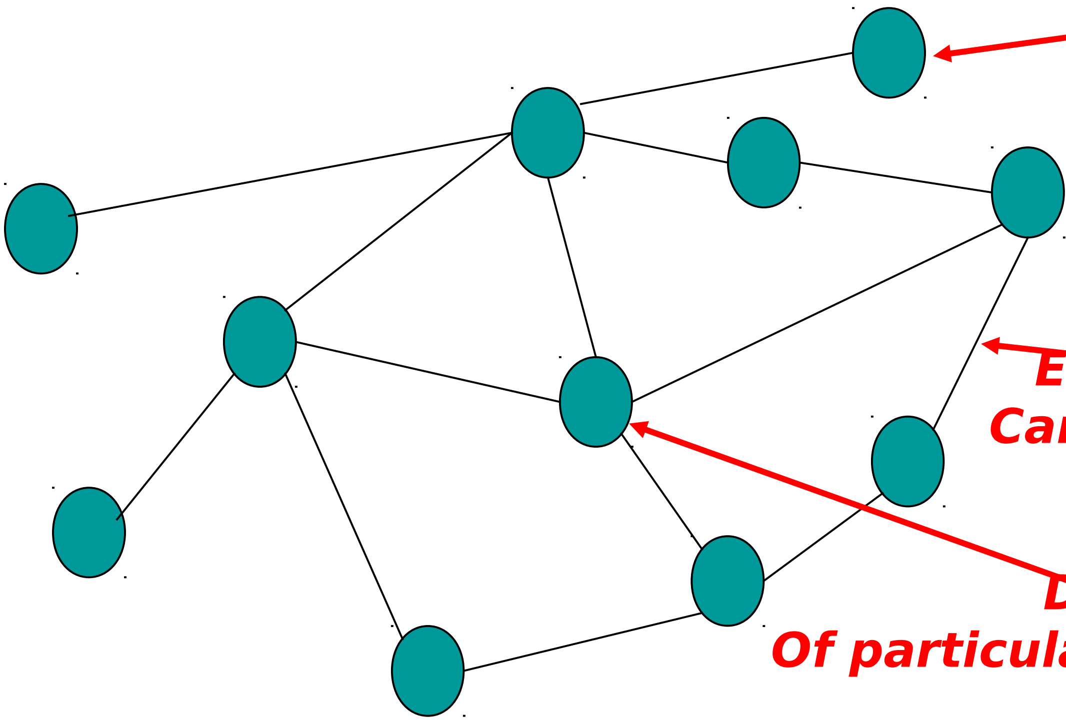
Other Complex Networks



- Internet
- Power grid
- Transportation
- Mobile Ad-hoc Networks (MANETs)
- Social (friends, tribes, organizations, towns, cities, countries, global village)
- Insect (bees, ants, wasps and other swarms)
- Ecosystems
- Cellular (neuronal)
- Molecular (metabolic)

Robust yet Fragile

Abstract Model of Networks



Vertex (node, site, cell)

Edge (bond, link, interaction)
Can be weighted and/or directe

Degree (connectivity)
Of particular interest: degree distributi

Diameter = length (# edges) in longest path between two vertices

- ***Qualitative attributes* - Complexity, scaling, topology**
- ***Performance metrics* - Latency, efficiency, accuracy, fault-tolerance, scalability**

Frank Doyle, ICB, University of CA at Santa Barb

Graph theory is a heuristic tool

Network Matrix to Abstract Model

	Vertex/Node	Edge/Link	Degree	Diameter
Internet	Routers, hosts	Fibers/coaxial cables/ copper	Number of routers directly connecting to a given router	Number of links in the longest "optimal" path, latencies across network
MANETs (wireless)	Wireless nodes, sensors, actuators, wireless routers	Strength of wireless radiations, interference patterns in conflict graphs	Number of nodes directly in the carrier range of a given node	Number of hops in the longest "optimal" path, latencies
Insects (swarms)	Individual insect	Signaling (chemical, visual)	Number of insects communicating with a given individual insect	Measure of breadth of interactions in a collection of insects
Brain/ Cellular	Cells (neurons)	Synaptic connection	Number of neurons linked to a given neuron (# axons projecting onto dendrites of a given cell	Measure of breadth of interactions in a collection of neurons
Cells/ Molecular	Proteins	Interaction (biochemical reaction or transformation)	Number of proteins linked to a given protein	Measure of scale of interactome (modularity and connectivity in the network)

Networking Structural Characteristics of Complex Systems

Robustness

- **Redundancy -- duplicate pathways create a simple form of robustness**
- **Recurring circuits -- negative feedback for stability and tracking; positive feedback for enhanced sensitivity**
- **Modularity -- encapsulation of functions into simpler units yields better failsafe designs**
- **Hierarchies and protocols -- distributing functionality across different levels in the network to manage complexity**

Fragility

- **Systems that are robust face fragility and performance setback as an inherent trade-off**
- **In control loops with negative, positive or combinations of feedback, unexpected perturbations can lead to catastrophic failure**

Network Matrix to Structural Characteristics

	Modularity	Recurring Circuits	Hierarchies & Protocols	Redundar
Intern et	Autonomous system, protocols layering, horizontal/vertical decomposition	Layering/abstractio n, feedback (TCP/AQM, ARQ, IP routing), soft state for reliability and robustness	TCP/IP protocol suite (application/transpo rt/ network/link/physic s)	Backup nodes, links, or paths that dynamically recover from failure based on feedback (e.g., IP routing, TCP)
MANETs (wireless)	Self-organized cluster of wireless nodes	Feedback, e.g., TCP/AQM, power control, ARQ, routing	TCP/IP protocol suite (application/transp ort/network/link/p hysics)	Backup nodes, links or paths
Insects (swarms)	Insect colony/beehive	Distributed feedback algorithms – bees recruit to explore food sources & prevent overcrowding food source	Delineation in an ant colony of queens, workers and soldiers	Re-marking of pheromone trails by ants
Brain/ Cellular	Localized clustering of function (memory, learning, visual-motor, etc.) in brain regions	Feedback and feed-forward projections in neuronal architectures	Sympathetic and parasympathetic limbs for managing blood pressure control	Neurons that encode for a signal (e.g., baroreceptor) are typically redundant and overlapping in sensitivity
Cells/ Molecular	Clusters observed in protein interactions that correspond to different localization (in cell) or function	Switches, oscillators, amplifiers are canonical recurring units in gene networks	Layers of control that include protein inventory control, separate from protein activity control	Genes that are duplicated or have heavily overlapping functionality

What is the Underlying Network Theory?

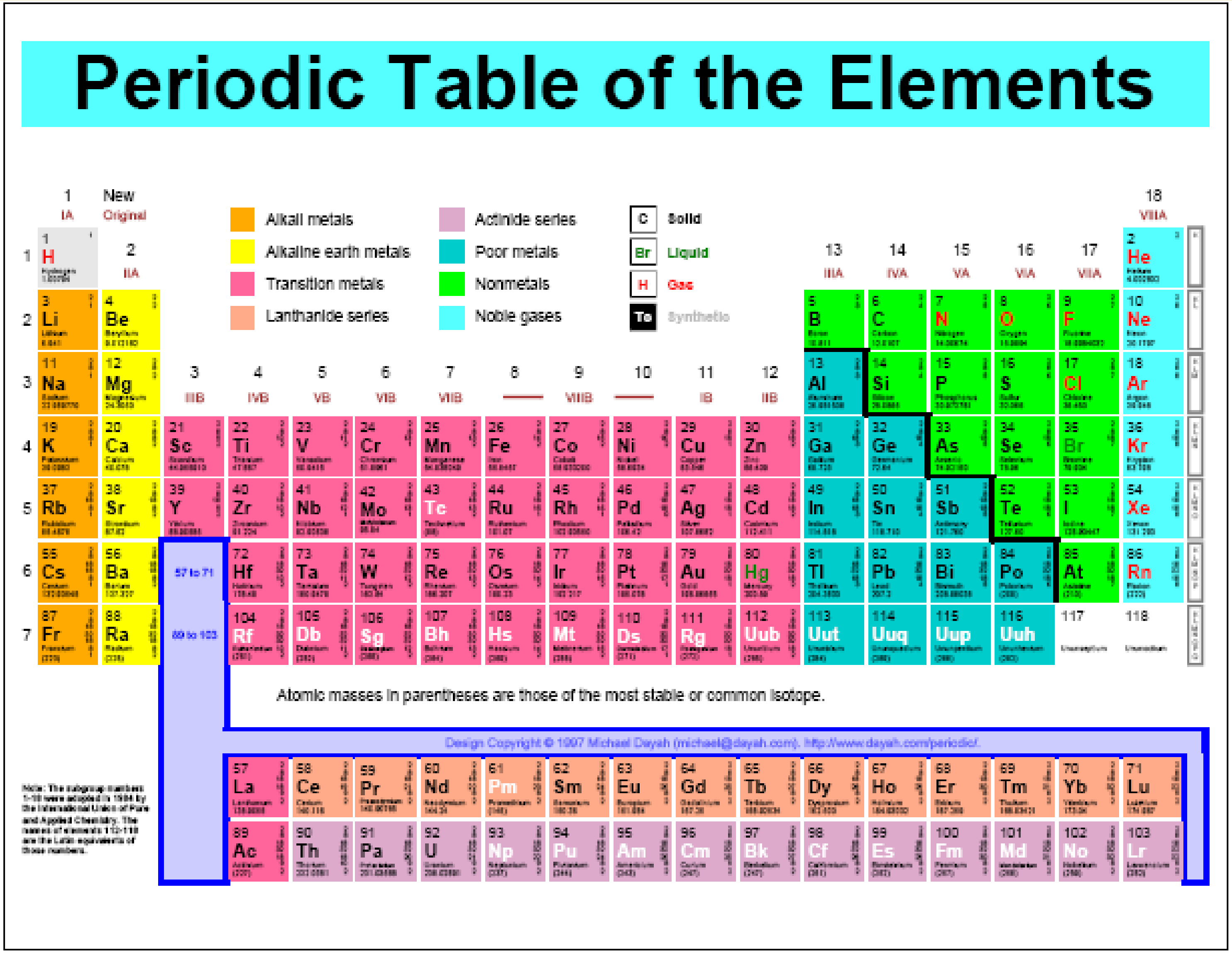
- Do seemingly diverse systems that exhibit network behavior have the same or similar underlying rules and principles?

- Is there a common language that can give us insight into the behaviors for these systems?

- Is th
  form of

New theoretical foundation for complex networks is needed

Mendeleyev’s Contribution to Scie



Summary

- ***Recent experience makes a compelling case that there is a need to address the challenges of Irregular Warfare***

- ***Investing across key frontier areas of science can provide the synergies to realize disruptive capabilities that can overcome the challenges of Irregular Warfare***

- ***As in the past, the Army's basic research program will provide technology options in realizing extraordinary capabilities for our***

"Our conventional modernization goals should be tied to the actual and prospective capabilities of known future adversaries – not by what might be technologically feasible for a potential adversary given unlimited time and resources." -- Defense Budget Recommendation Statement , Secretary of Defense Robert M. Gates